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FORBIDDEN LINE WAVELENGTHS AND TRANSITION PROBABILITIES MEASURED USING AN ELECTRON BEAM ION TRAP (EBIT)

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1. Introduction

Several coronal lines posed a long-standing riddle to earth-bound spectroscopists, until - following up on a suggestion by Grotrian (1937) - B. Edlén (1942) confirmed that their wavenumbers indeed corresponded to fine structure intervals in the ground configurations of highly charged ions like Fe X and Fe XI. This in turn caused turmoil in solar physics, because the corona must be much hotter than the underlying chromosphere in order to produce such ions,.

X-ray and EUV spectra of the sun became available after World War II, by observations from sounding rockets and satellites. These spectra confirmed the presence of the highly charged ions. Laboratory observation of the (electric-dipole) forbidden lines, however, had to wait for the development of low-density plasma discharges like the tokamak fusion experiments, because in regular light sources, collisions would likely quench such long-lived levels. Since then, a fair number of forbidden transitions has been observed in the laboratory, and forbidden lines are being valued for plasma diagnostics.

While forbidden transitions in light ions are often found in astrophysical light sources, similar transitions in highly charged heavy ions like Kr will be important for plasma machines like ITER, in which Kr will likely be used for radiative cooling and will therefore also be available for detailed diagnostics.

2. EBIT

Electron beam ion traps (EBIT) now offer novel ways to study such forbidden transitions:
a) EBIT can produce any charge state ion of any element, with much simpler access and more elemental flexibility than at a large-scale fusion-oriented tokamak or similar plasma experiment.
b) EBIT can be switched from EBIT mode (with the electron beam on) to magnetic trapping mode (electron beam off, then working like a Penning ion trap) in less than 1 ms, permitting time-resolved studies and atomic lifetime measurements.

In explorative studies of visible spectra from the NIST and LLNL electron beam ion traps, a variety of ion species has been excited and stored. The spectra (see the Ar spectrum in Figure 1, or Träbert *et al.* 1998 for spectra of Kr) are dominated by a number of forbidden lines.

Among the transitions studied for their wavelengths are the the $3s^23p^2$ $^3P_1$ - $^3P_2$ transition in Si-like Kr^{22+} and Mo^{28+}, and the $3d^4$ $^5D_2$ - $^5D_3$ transition in several Ti-like ions from Xe^{32+} to Au^{57+} (Figure 2). The measured wavelengths, in comparison to calculated data, help to improve isoelectronic predictions for elements which may be present in future fusion test plasmas.

On several forbidden lines (the ground state fine structure transition in Ar^{13+} and the $3s^23p^2$ $^3P_1$ - $^3P_2$ transition in Si-like Kr^{22+}), transition probabilities have been measured , with about 5% uncertainties (Serpa *et al.* 1997, Serpa *et al.* 1998, Träbert *et al.* 1998). This is more precise than the predictions from most *ab initio* calculations (Cheng *et al.* 1979, Biémont and Bromage 1983, Huang 1985, Verhey *et al.* 1987), which usually need to be corrected for experimental fine structure intervals. However, better spectral resolution and improved light collection will be needed (and are in reach) to reach the desired level of 1% uncertainty.

Table 1. Results of Lifetime Measurements using EBIT

Ion	Upper level	Lifetime (ms) Experiment		Lifetime (ms) Theory as is	Theory after energy correction
Ar^{13+}	$2s^22p$ $^2P^o_{3/2}$	8.7±0.5	NIST	9.62 a	
				9.51 b	
				9.41 c	9.58
Kr^{22+}	$3s^23p^2$ $^3P_2$	5.7±0.5	NIST	6.46 d	6.78
		6.3±0.3	LLNL	5.83 e	6.69
Xe^{32+}	$3d^4$ $^5D_3$	2.15±0.14	NIST	2.4 f	

a	Verhey *et al.* 1987	b	Froese Fischer 1983	c	Cheng *et al.* 1979
d	Biémont and Bromage 1983	e	Huang 1985	f	Feldman *et al.* 1991

3. Conclusion

Electron beam ion traps are quite suitable for the observation of forbidden transitions in the visible and permit lifetime measurements in the millisecond range. The precision for lifetime measurements reached so far is about 5%. In the x-ray range (with better detection efficiency and lower detector noise), EBIT has meanwhile yielded the first lifetime data with sub-percent precision. It is expected that after further development work at least the 1% range of uncertainty will be reached also for forbidden transitions in the visible spectrum. This is better than most applications require and severely tests theory.

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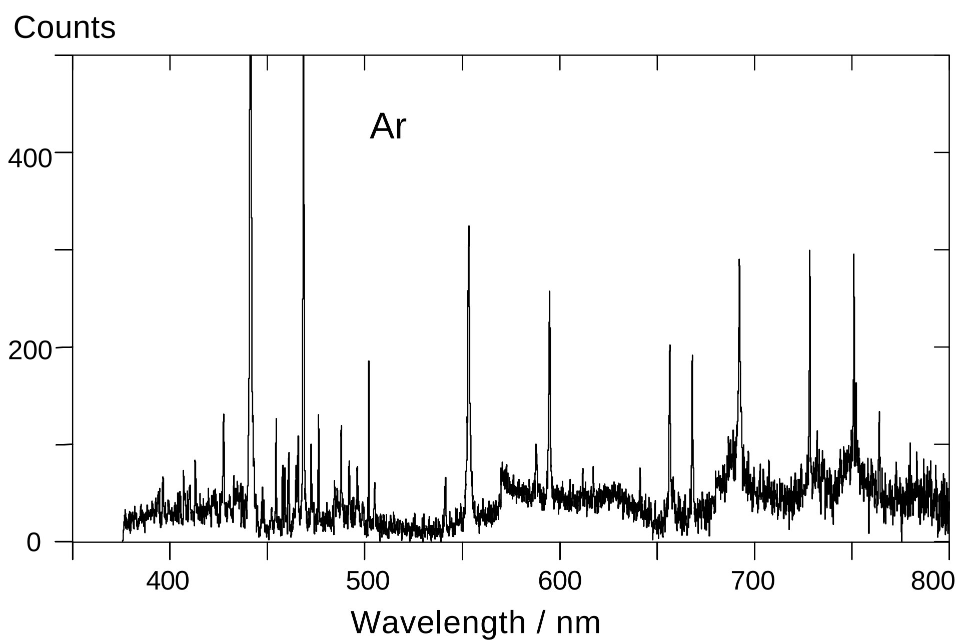

Fig. 1.-- Composite spectrum of Ar, measured at the LLNL SuperEBIT using a 1m normal incidence spectrometer equipped with a CCD camera (from Träbert *et al.* 1998).

Fig. 2. -- Isoelectronic trend of the $3d^4\ ^5D_2 - ^5D_3$ transition wavelength in Ti-like ions. Full line: Prediction by Feldman et al. (1991). Experimental data for Xe measured at NIST Morgan *et al.* 1995, Serpa *et al.* 1996), for Ba at NIST (Morgan *et al.* 1995) and at Oxford (Bieber *et al.* 1997), for Nd and Gd at NIST (Serpa *et al.* 1996) and for Au at LLNL (Träbert *et al.* 1998). Later MCDF calculations by Beck (1997) come closer to existing experimental results for Xe to Gd than the initial calculations by Feldman *et al.*, but give no further predictions.